United States Naval Postgraduate School

THESIS

A SEARCH FOR THE ELECTROPHONIC PHENOMENA IN THE MICROWATT POWER DOMAIN

by

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June 1971

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Phenomena in the Microwatt Power Domain

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ABSTRACT

The physiological sensation of hearing can be stimulated by an alternating current applied to the head using small electrodes. The major disadvantages of systems of this type have been the large magnitude of driving voltage required, ~ 100 to 4000 volts, and the magnitude of power dissipated in the head, ~ 1 watt.

The objectives of the paper were to investigate the basic phenomena and to attempt to find a low power method for production.

Previous successful experiments were reproduced during the basic investigation phase. Selected combinations of signal types and electrodes were then tested.

An extremely low power mode of operation was found and documented. Threshold values for a single tone were found to be in the order of 10μA at 10μWatt making an extremely small low cost hearing aid a possible application.

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I. INTRODUCTION

"Of all the organs of the body, few accomplish as much in so little space as the ear. If an engineer were to duplicate its function, he would have to compress into approximately one cubic inch a sound system that included an impedance matcher, a wide-range mechanical analyzer, a mobile relay-and-amplification unit, a multichannel transducer to convert mechanical energy to electrical energy, a system to maintain a delicate hydraulic balance, and an internal two-way communications system. Even if he could perform this miracle of miniaturization, he probably could not hope to match the ear's performance. It can set itself to hear the low throb of a foghorn at one end of its range and the piercing wail of a jet engine at the other end. It can make the fine distinction between the music played by the violin and the viola sections of a symphony orchestra. It can reject the hubbub of a cocktail party while picking out a single familiar voice. Even during sleep the ear functions with incredible efficiency: because the brain can interpret and select signals passed to it by the ear, a man can sleep soundly through noisy traffic and the blaring of a neighbor's television set - and then awaken promptly at the gently urging of a chime alarm clock." [Ref. 1]

The physiological sensation of hearing can be stimulated by an alternating current applied to the head using small electrodes. In this thesis, this phenomena shall be called "Electrophonic Hearing."

The objectives of this paper are:

1. To investigate the basic phenomena.

2. To investigate threshold levels for various electrical signals.

3. To investigate threshold levels for various electrode configurations and compositions.

4. To attempt to find a low power mode of operation.

A communications head set utilizing this phenomena in a lower power mode could have the following advantages:

1. It could be light, yet completely self-contained operating from a small battery.

2. It would be reliable since it would have few parts, none of which are moving.

3. Simplicity of circuitry, design, and manufacture would make such a set relatively inexpensive.

4. It has been shown that this type device could enhance normal hearing in high noise environment when used with ear plugs and suppressors [Ref.2].

5. Military watch standers who must wear standard headsets over their ears for any length of time would

welcome these devices which could be worn comfortably behind the ears.

6. It would greatly improve the ability of a man to carry on a normal conversation while guarding a radio net.

7. All things considered, it might become a logical replacement for the standard Navy headset.

8. It would be a logical and efficient replacement for all types of bone conduction type hearing aids.

Hence, an investigation was launched to attempt to apply the electrophonic phenomena in the solid state range and to devise a configuration to provide the above listed advantages.

At present, there are two "systems" which use this effect for communications. One is the "NAACH," (non accoustic audio coupling to the head), a product of NADC, Johnsville [Ref.3]. The basic system is shown below.

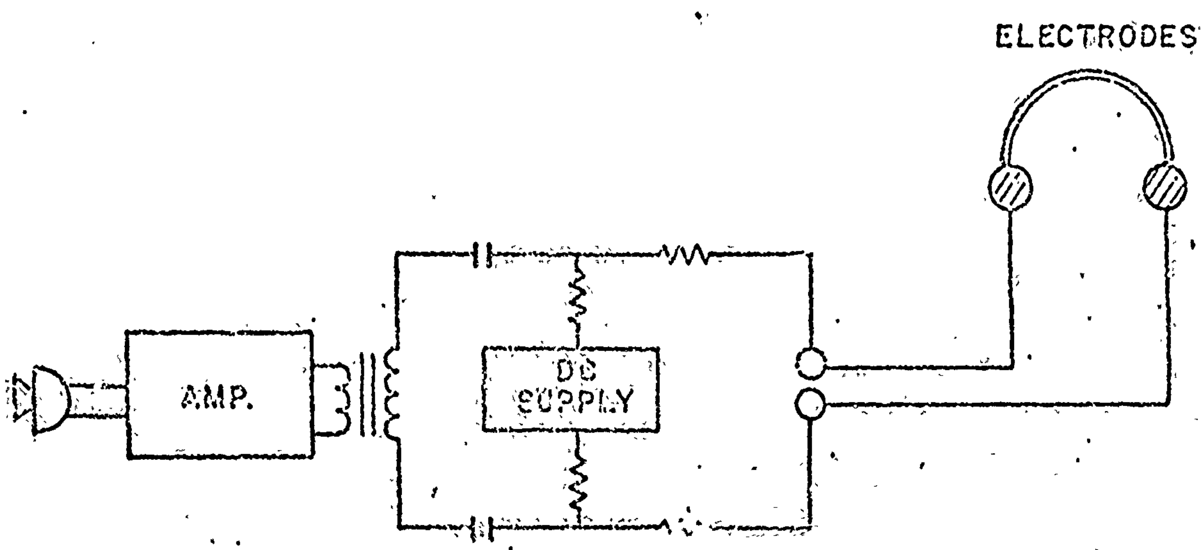

Figure 1. Non Accoustic Audio Coupling to the Head [Ref.3]

The audio amplifier provides up to 4000 V of audio signal, and the D.C. power supply provides ≈ 230 volts bias.

The input power to the head is in the order of watts and is coupled capacitively through two electrodes both covered with 35 mil dielectric material. The agnitude of the voltages and power preclude the use of this system as a self-contained unit.

The second of the two units is the "Transdermaphone," built by Skinner of the Naval Postgraduate School [Ref.4]. This device is a follow on of the research of Puharich [Ref.2] and is very similar in operating parameters to the research instrument which Puharich has now made commercially available.[1] The "Transdermaphone" provides audio modulation of a 100 kc carrier. The drive voltage is ≈ 400 volts to two electrodes covered with 1/2 mil of milar.

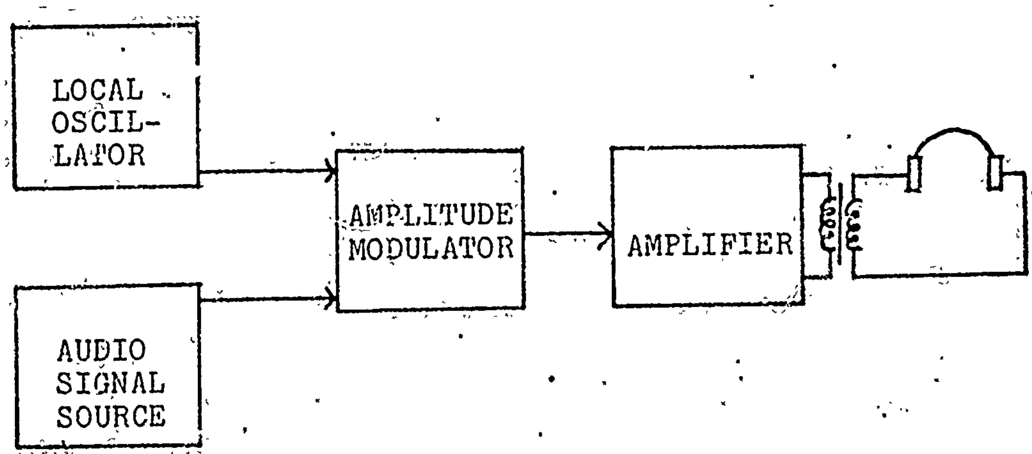

Figure 2. Transdermaphone

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[1] Intelectron Corp., 432 W. 45th Street, New York, New York 10036.

The input power to the head is again in the order of watts. The bulk of the circuitry and components required preclude the possibility of a compact, self-contained package.

The review of previous research shows that the above, and several different methods, have yielded some success, and that further investigation of the phenomena might lead to new techniques, particularly directed to much lower power requirements.

Before proceeding further it is necessary to have a basic working knowledge of the operation of the ear. This information is contained in the following section.

II. BASIC OPERATION OF EAR

The ear may be divided into three parts: the external ear, the middle ear, and the internal ear.

The external ear consists of the pinna and the external auditory meatus, the latter a tube closed at one end by the tympanic membrane (ear drum).

The middle ear is made up of the tympanic membrane and the ossicular chain, consisting of the malleus, incus, and stapes. These elements are small bones contained within the middle ear cavity. This air-filled cavity in the temporal bone is normally closed, although it may be equalized to external pressure via the eustachian tube, which opens to the back of the throat. Thus, normally, in spite of the local atmospheric pressure, the tympanic membrane will not have a bias pressure due to a difference in the pressure inside and outside the middle ear.

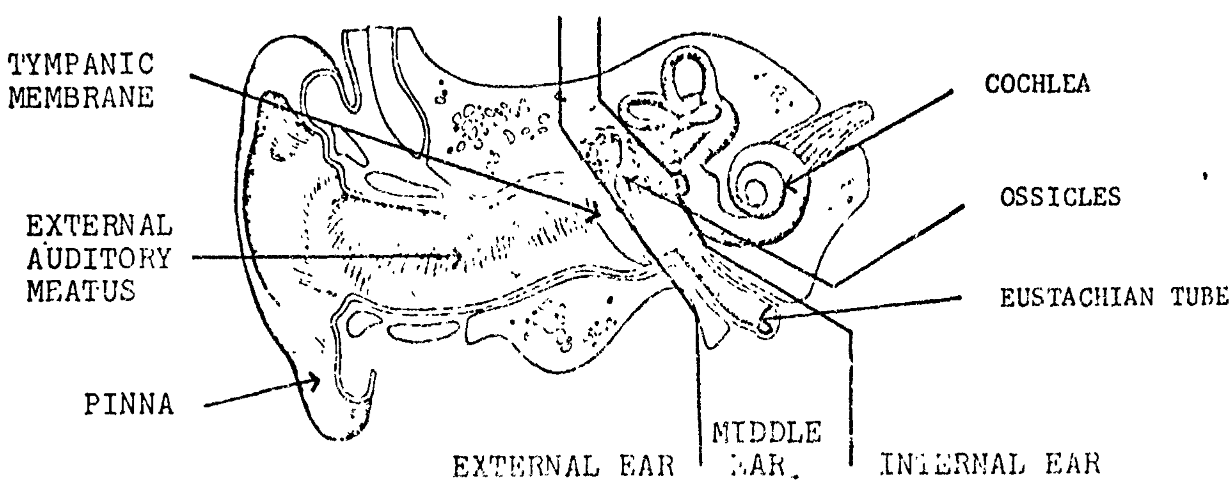

Figure 3. Illustration of Ear

The tympanic membrane is a flexible structure which closes the external auditory meatus. Rigidly attached to this membrane is the malleus.

The malleus is in turn attached to the incus, which is in turn attached to, and transmits motion to, the stapes. This mechanical lever system acts as a pressure transformer between the external and internal ear. This transformer action is quite important as the tympanic membrane is a pressure transducer operating in air, while the stapes, which drives the oval window of the cochlea, is a transducer operating on a liquid. Thus the tympanic membrane and the ossicles provide an efficient impedance match between the two mediums, air and liquid.

The internal ear is located within the temporal bone and is made up of two connected parts, the semi-circular canals and the cochlea.

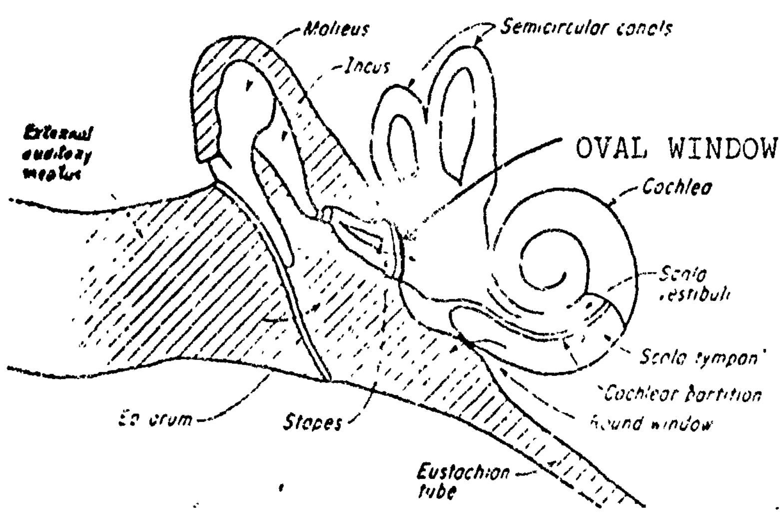

Figure 4. Illustration of Inner Ear

The cochlea consists of a spiral cavity containing fluid, various membranes, and the sensory elements of sound detection. The cochlear cavity is coupled to the middle ear by two openings, or windows, in the bone. These openings, the oval window, and the round window, are each closed by a flexible membrane in the window which isolates the middle and internal ear. The stapes of the ossicular chain is attached to the membrane of the oval window as previously described. The round window and its membrane serve as a pressure relief for the cochlea.

The spiraled cavity of the cochlea is divided along nearly its entire length by the cochlear duct. This flexible enclosure lies between two additional chambers, or scalae.

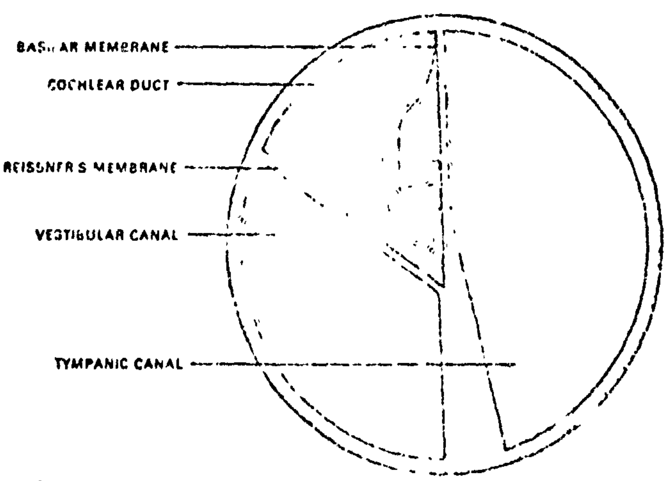

Figure 5. Cross Section of Cochlear tube

These two chambers are the scala vestibuli, bounded at the bottom end by the oval window, and the scala tympani which is bounded by the round window. At the top or apical end of the cochlea there is an area where the cochlea duct is not present and the two scalae are connected directly together. This is the helicotrema. The helicotrema prevents a fixed pressure from existing between the two scalae and thus across the cochlear duct.

The cochlear duct is itself filled with fluid and made up or bounded by the two membranes, Reissner's membrane, and the basilar membrane. It is in latter membrane that the sensory structures of the ear are imbedded. It is the characteristic of the cochlear duct, and especially of the basilar membrane, that determines the frequency localization characteristics along the cochlea.

At this point it is possible to trace the auditory signal from its source to a signal from the cochlea. Sound vibrations strike the head and pinna, traverse the external meatus, and excite the tympanic membrane. Movement of the tympanic membrane causes motion of the stapes through the mechanical linkage of the ossicles. When the stapes moves it induces fluid motion causing a sequence of traveling waves to traverse the scalae and excite the cochlear duct. This motion excites the sensory receptors within the cochlear duct and causes a neural output.

The cochlear duct has roughly a triangular cross section and extends from the basal end to the apical end of the cochlea, where the helicotrema is located.

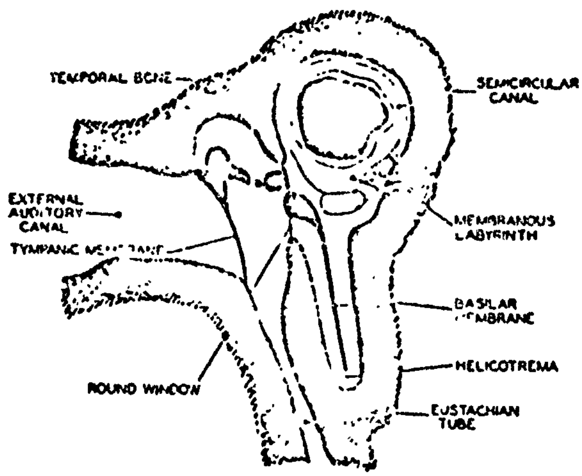

Figure 6. Inner Ear with Unspiralled Cochlea

The scalae vestibuli and the scalea tympani are filled with perilymph, a fluid having a density and a coefficient of viscosity about the same as blood plasma. The cochlear duct contains endolymph, a heavier, more viscous fluid. The basilar membrane is a fibrous, thick elastic membrane extending from the bony shelf to the spiral ligament. Reissner's membrane is very thin and flexible [Ref.5].

The organ of Corti, lying on the basilar membrane, contains about 20,000 hair cells with each cell containing four or five hair-like elements. One end of each of these hairs extends through the reticular lamina to the tectorial membrane and is embedded there.

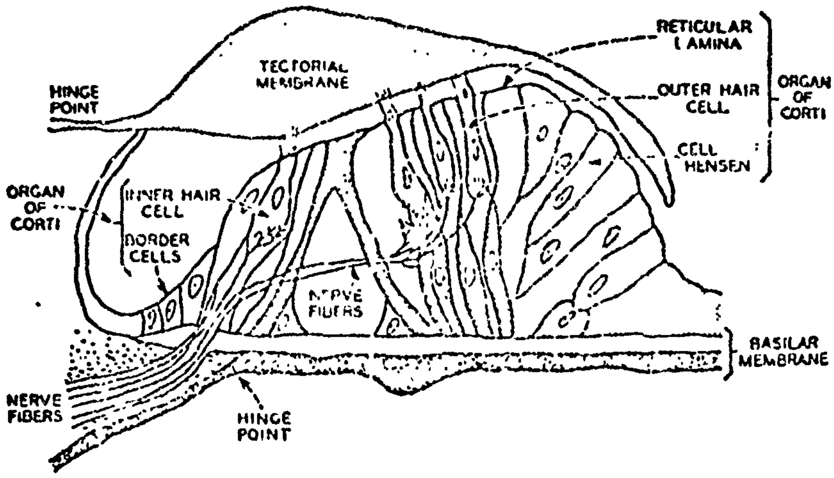

Figure 7. Organ of Corti

The tectorial membrane is composed of a system of diagonal fibers and a jelly-like material that yields to show movements, but is resistant to quick movements. It is hinged at one side [Ref.5].

Motion of the basilar membrane creates a shearing action between the tectorial membrane and reticular lamina. This shearing motion bends the hairs. Associated with each hair are sensory cells in the Organ of Corti. The sensory cells respond to the bending of the hair with electrical potential changes which in turn are translated into action potentials carried to the brain via the VIIIth Cranial nerve.

In the process of transducing the accoustical waves, an analog electrical signal is developed in the cochlea. By placing electrodes on the round window and the oval window, a voltage waveform may be observed which is of the same frequency and magnitude as the impinging sound wave. Thus the cochlea acts as a microphone [Ref.5].

On the other hand, the train of action impulses delivered to the brain is not an analog signal, but consists of a sequence of pulses. The repetition rate of these pulses can follow frequencies of stimulation in the low range of the hearing spectrum.

Since an individual nerve fiber can not conduct more than ≈ 1000 pulses per second, this one to one correspondence starts to break up at ≈ 1000 Hz and no longer holds above ≈ 3000 Hz.

III. CHRONOLOGICAL HISTORY OF ELECTROPHONIC/MICROPHONIC RESEARCH

Over the years many authors have researched the interesting phenomena of electrophonic audio stimulation.

Historically, Volta was the first to experiment with electro-stimulation. Using his newly invented voltaic cells, he investigated th possibility of using direct currents as a possible means of communication [Ref.6]. Upon connecting a battery of 30 or 40 "couples," he closed the switch and produced a D.C. current between two metal rods which he had inserted into his ears. He reported "a jolt in the head," after which he heard a noise like the "boiling of soup." Apparently the experiment was unduly uncomfortable, for Volta did not pursue it further.

It was in 1930, that the basis of current research was established. Wever and Bray first described certain electrical phenomena occurring in the accoustic nerve during the reception of auditory stimuli. This effect consists of a voltage waveform at a frequency corresponding to that of the stimulating sound. With amplification, speech is reproduced, and the voice of the speaker can be recognized. They concluded correctly that it was dependent upon the functional integrity of the cochlea. Their now classic experiments involved surgically implanting electrodes in the inner ear of a live cat, and then using the cat's ear as a microphone to drive a loud speaker system at an Accoustical Engineers convention [Ref.7].

Davis and Saul followed the work of Wever and Bray and were able to show that the cochlea, not the accoustic nerve was the origin of these "cochlear microphonics." [Ref.8]

Many of the electromechanical transducers found in nature (Pizzo-electric crystal) are, in fact, reversible. With this point of view Stevens [Ref.9] in 1937 attempted to externally stimulate the cochlea with a voltage waveform. A defect in early attempts at external stimulation was that direct current was used. With A.C. currents Stevens was able to simulate audition and established the first thresholds for "electrophonic hearing."

These signals were applied by filling the ear with a half molar salt solution, inserting a small brass electrode into the solution, and strapping another electrode (a brass plate) to the wrist with a conducting paste. The electrode on the wrist, called the indifferent electrode, was connected to ground. This procedure was called the "Brenner Method."

The sounds heard by Stevens and his researchers were poor, due to large amounts of distortion caused by the predominance of second harmonics. In 1939, Stevens observed that by applying a positive D.C. potential to the active electrode, the power of the second harmonic could be reduced, and that of the fundamental increased reducing the distortion greatly. A negative D.C. potential to the active electrode had the opposite effect [Ref.10].

Replacing the test oscillator with a radio, with no polarizing voltage, the observer heard speech as an unintelligible sequence of sounds. But, as soon as a D.C. potential of about +1.5 volts was applied, the speech became clear and understandable [Ref.10].

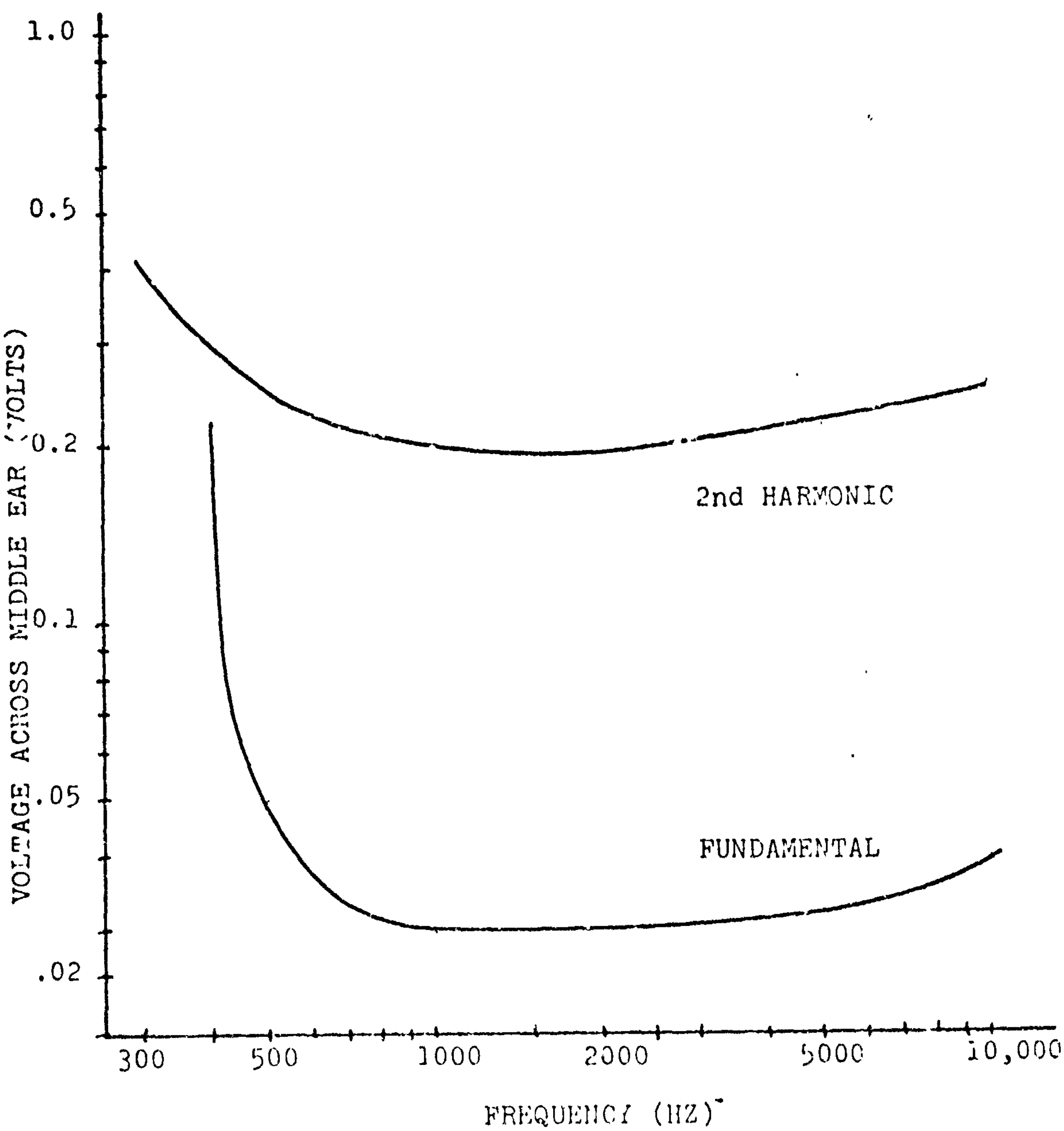

Figure 8. Frequency vs. Voltage for Threshold of Hearing Using Brenner Method.

This figure illustrates how the electrical threshold varies with the perceived frequency. The upper curve shows the voltage across the middle ear needed for the observer to hear the second harmonic when the fundamental has been suppressed by a negative D.C. polarizing voltage. The abscissa shows the frequency perceived under these conditions (the applied frequency was always an octave lower). The lower curve shows the voltage needed for the observer to hear the fundamental frequency component when a positive D.C. polarizing voltage of 1.2 volts is applied between the electrodes, in which case the applied frequency is indicated by the abscissa. The Brenner method was used in this experiment.

In 1940 Jones, Stevens, and Lurie demonstrated that when an A.C. signal is passed through the head via a salt solution in the external ear canal, a normal observer hears a tone which is related to the stimulus by a square law [Ref.11]. That is, if the sound heard is interpreted in terms of motion of the tympanic membrane, then the displacement of the membrane is proportional to the square of the instantaneous voltage.

These writers suggested the hypothesis that the cavity formed by the middle ear acts as an electro-static transducer. This hypothesis accounted for the square law response and for certain quantitative aspects of the results. This idea has to meet the objection, however, that persons without tympanic membranes are able to hear by electrical stimulation. In order to determine the relation between the hearing of normal subjects and those lacking tympanic membranes, 18 ears lacking tympanic membranes were stimulated electrically. Eleven ears heard pure tones corresponding in pitch to the frequency of the applied voltage; seven heard a puzzling noise whose character was roughly independent of the stimulating frequency. Examination showed that the pure-tone response in the operated ears was purely linear, independent of D.C. bias in contradiction to the quadratic response of normal ears. Hence, under electrical stimulation normal and operated ears hear by means of two distinctly different mechanisms. The square law response in normal ears is apparently mediated by an electro-static action in the middle ear. The linear response in operated ears may well be due to direct stimulation of the cochlear openings.

Evidence was also presented that direct stimulation of the auditory nerve, bypassing the cochlea, results only in random noise, independent of stimulus frequency [Ref.11].

Kellaway during research in 1940 determined:

1. Monaural beats may arise when an electrical and a mechanical stimulus are applied to the same ear.

2. The psychological attributes ascribed to the sensations produced by the interaction of two stimuli (beats) with varying degrees of difference in their frequencies are essentially similar whether two mechanical stimuli or a mechanical and an electrical stimulus are used.

3. When a mechanical and an electrical stimulus of identical frequency are applied to the ear, it is possible to cancel the one by adjusting the phase and intensity of the other [Ref.12].

These observations lead Kellaway and others to conclude that the two types of stimuli, mechanical and electrical, activate the same cochlear elements and that the activating force is mechanical in both cases.

Probably the most significant name in recent research of audition is that of Georg Von Bekesy. He was awarded the Nobel Prize in 1961 for his studies of the "traveling wave" in the interior of the cochlea.

In 1950-1952 Bekesy made great strides in investigating the electrophysiology of the cochlea. His results indicated that the endolymph is surrounded by an electrically insulating layer and that the inner part of the Organ of Corti is almost completely protected from external electrical fields. The only areas not so insulated are the round and oval windows [Ref.13]. He also indicated that for parts of the cochlea near these two windows the cochlear tube can be considered electrically as a transmission line [Ref.14].

This would seem to indicate that to induce electrophonic hearing we must couple an electrical signal either directly or indirectly to the round and oval windows.

Flottorp, working at Harvard under a Navy contract in 1952 researched and tabulated five separate phenomena associated with electrophonic hearing by means of an externally applied stimulus [Ref.15]. He was the first to seriously research the "fricative" effect. With a moving electrode on the skin or on the roof of the mouth the observer receives a much stronger sensation of hearing. Other configurations included a large area electrode on the head, either wet or dry; the usual salt solution filled ear with immersed electrode; an electrode in contact with mucous tissue inside middle ear; or an electrode in contact with epidermis of the meatus.

His results indicated that the hearing of a tone under any of the above five conditions is probably due to vibrations set up outside the cochlea, although there appear to be at least four different transducing mechanisms. Contrary to previous research he surmised the tympanic membrane not to be involved in the conversion of electrical energy into mechanical vibration.

In 1964 Puharich and Lawrence documented another method of stimulation first investigated by Stevens in 1937. They amplitude modulated a 100 KHz carrier with successful result The 100 KHz carrier apparently performed the same biological function as the D.C. bias [Ref.2].

They named their process "Transdermal Stimulation" and now manufacture amplitude modulated research instruments using electrodes covered with Milar (capacitively coupled), with audio thresholds for single tones in the 10^{-1} watt region.

Sommer and Von Gierke took a hard look at "transdermal stimulation" later in 1964 in a study of the hearing phenomena in electro-static fields. In this study the head or parts of its surface were exposed to an audio-modulated alternating electro-static field with and without a superimposed D.C. field. The threshold data collected indicates there is no other auditory stimulation excepting mechanical tissue excitation by the electro-static forces produced by such fields [Ref.16].

In 1964 Harvey and Hamilton, following the research of Sommer and Von Gierke, presented data indicating strongly that the mechanism of hearing in an amplitude modulated radio frequency field consists only of bone conducted tissue vibrations to the cochlea produced by the electro-mechanical pressures in the field [Ref.17].

Skinner, of the Naval Postgraduate School, built his "Transdermaphone" in 1968. This device based on the research of Puharich, utilized an amplitude modulated 100 KHz carrier, and has been used to demonstrate and research several of the existing phenomena [Ref.4].

Returning to the non-AM configuration, the Naval Air Development Center of Johnsville, Pennsylvania, developed the "NAACH" in late 1969. This was possibly the first attempt to incorporate the basic phenomena into a communications system [Ref.3].

IV. DISCUSSION OF PREVIOUS EXPERIMENTAL RESEARCH

In the aforementioned research the efforts were in large part an attempt to find an external system to simulate audition by using electrodes on or near the head.

Reviewing the basic design parameters of these investigations two major groups of variables were observed and are indicated below.

A. BASIC TYPES OF ELECTRICAL SYSTEMS

1. Audio Frequency Stimulation System

With one exception all experimental systems of this type indicated that the response to stimulation by audio frequencies result in large amounts of distortion produced by second harmonics. The exception is in the case where the observer has no tympanic membrane, and via the Brenner method is able to have the electrical signal impinge directly upon the round and oval windows. This is probably the only case of true inverse cochlear microphonics.

2. Audio Frequency Stimulation Plus a D.C. Bias System

It can be shown mathematically [Ref.4] that if the head is considered a dielectric between two plates (electrodes) of a capacitor with one plate to the ground that the addition of a positive D.C. bias to the active electrode will enhance the fundamental and reduce the second harmonic and subsequently the distortion. A negative D.C. bias has the opposite effect.

3. Audio Modulation of a Radio Frequency System

Apparently A.M. produces the same biological effect in stimulation as does the D.C. bias. Additionally, however, this indicates that there must be a biological detector that demodulates the signal prior to the reception of the stimulus.

4. Audio Frequency Plus an A.C. Bias

This previously untested method involves the linear addition of the audio signal to a constant radio frequency. Experiments indicated that this system was no more advantageous than audio with a D.C. bias.

B. BASIC ELECTRODE CONFIGURATION AND COMPOSITION

1. Capacitively Coupled Electrodes

These electrodes, mostly metal, covered with some dielectric, evoked undistorted audition when used with a positive D.C. bias to the active electrode or amplitude modulation.

The input power to the head with these types of electrodes is in all cases on the order of 1 watt.

2. Bare Electrodes

By using bare electrodes (uninsulated) the magnitudes of voltage and amperage needed for stimulation were greatly reduced. In the majority of cases, however, the threshold of pain is below the threshold of hearing. Among the many experiments, only Flottorp [Ref.16] recorded significant results using bare electrodes.

3. Direct Coupled Electrodes

In electrical systems the carrier of charges is the electron. In biological systems the charge carriers are ions. With bare electrodes the conversion of charge carriers from electrons to ions must take place in the interface between the electrode and the skin.

As indicated by Dr. Marmont of the Naval Postgraduate School, it can be shown, that dependent upon the material of the electrode, a gas or fluid barrier can build up between the electrode and the skin. This fact is borne out by several scientists who indicate the decrease in stimulus with time, when applied with bare electrodes.

Consequently, to bypass this problem, direct coupled electrodes which convert electrons to ions prior to reaching the skin/electrode interface were fabricated. They consist of a chemically pure silver disc, plated with silver chloride. The silver chloride provides an abundant supply of chloride ions for transmission into the biological medium.

These types of direct coupled electrodes have been dubbed ionic electrodes. See Appendix A for fabrication details.

An observation of previous research which proves to have significance is that almost without exception, electrodes were consistently used in identical pairs.

V. EXPERIMENTAL PROCEDURES AND RESULTS

Gathering the variables and parameters of the previous investigators, a table was made of the possible combinations and permutations. A systematic theoretical investigation of the most interesting cases followed.

The factors considered were:

1. Type of system
   a. Pure Audio
   b. Audio plus D.C. Bias
   c. Audio Modulation of R.F. Carrier
   d. Audio plus R.F.
2. Signal Magnitude and Composition
   a. Voltage Levels
   b. Current Levels
   c. Frequency
   d. Percent of Modulation (when present).

The major number of variables arises from the myriad of different systems used to couple the electrical signal to the head. Briefly:

3. Electrodes
   a. Size
   b. Contact Pressure
   c. Location
   d. Number
   e. Configuration

f. Shape

g. Composition.

The theoretical combinations were compared and screened with the resulting list of proposed <u>experimental</u> combinations

1.. System (3 types)

a. Audio and D.C. bias

b. AM with 100 kc carrier, ≈ 50% modulation

c. Audio plus 100 kc

2. Total Power input to the head was to be limited to 500 milliwatts in any reasonable combination of voltage and amperage, consistent with low power requirements.

3. Electrodes, two 3/4" discs, stationary (5 types)

a. Direct Coupled Ionic, wet or dry (2)

b. Capacitively Coupled,covered with 1/2 mil milar(2)

c. Capacitively Coupled, covered with 1 mil milar (2)

d. Bare Metal (2)

e. One Ionic, wet or dry to ground and one capacitively coupled electrode covered with 1/4 mil milar.

4. Electrode Location (3 configurations)

a. Forward of each ear

b. Behind each ear

c. One electrode behind ear and one electrode to neck.

A circuit was built to drive the listed combinations; its schematic is shown in Appendix B. Skinner's Transdermaphone was used in the tests involving AM with capacitively coupled electrodes. The schematic of this device is shown in Appendix C. The instrumentation used for the observations and recording of data is shown in Appendix D.

Using the various combinations of indicated parameters, the majority of previously successful experiments were performed: The synthesized circuits proved to be very versatile and successful in driving the many different types of electrodes.

The wet ionic electrodes, when used as a pair, lowered the input impedance of the head an order or magnitude.[2] However, the threshold of pain was well below the threshold of hearing, in all four basic systems.

The addition of audio plus RF bias proved no more efficient than audio plus a D.C. bias.

In all cases placing the electrodes behind the ears achieved the best results.

Configurations using a D.C. bias showed that a positive D.C. bias to the active electrode improved the system, whereas a negative D.C. bias degraded it, which bears out earlier experiments.

At the end of the tests, with most combinations yielding negative results, one combination was observed to be markedly lower in both amperage and voltage required for audition.

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[2] $R_S = 219\Omega \qquad C_S = 71.4$ n F

The system was an audio signal plus D.C. bias with one dry ionic electrode, and one capacitively coupled electrode using a 1/4 mil milar dielectric. Both electrodes were placed behind the ears.

In reviewing previous experimental work, it appears this combination has been overlooked. Researchers have apparently worked with pairs of bare, or dielectric covered electrodes, but not with one of each.

It was immediately obvious that this was an interesting configuration, since the initial threshold determination at 6 KHz was 1.4 $V_{(RMS)}$, 40$\mu V_{(RMS)}$, and 56.0 μ watts. This is approximately 45 db below the power required by the transdermaphone and the NAACh.

A standard audio signal generator was found to provide a stimulus well in excess of that needed. Hence, the experimental circuitry was reduced drastically. The revised system and its components are shown below.

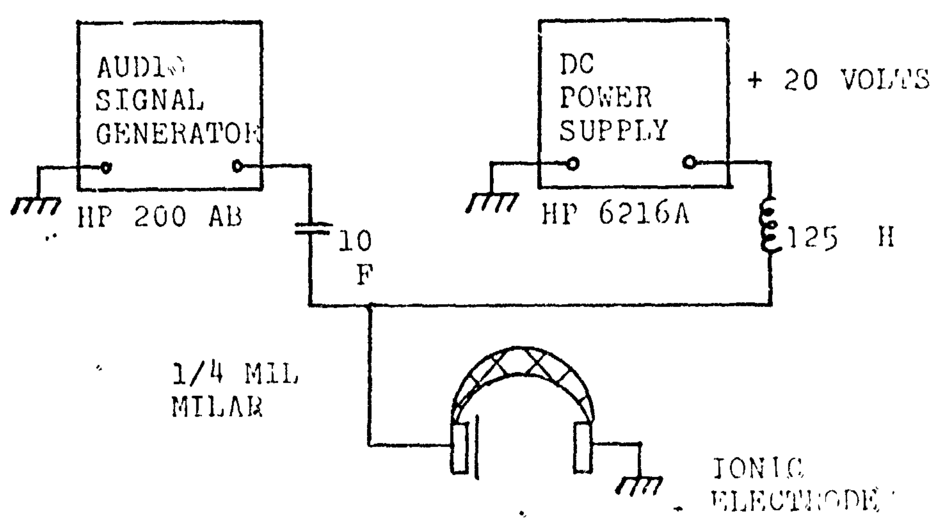

Figure 9. Electrophonic Effect with Low Power Mode

Subsequent tests were run on several observers to gain knowledge as to the threshold levels. The composite average threshold for 18 normal ears is shown in the following graphs.

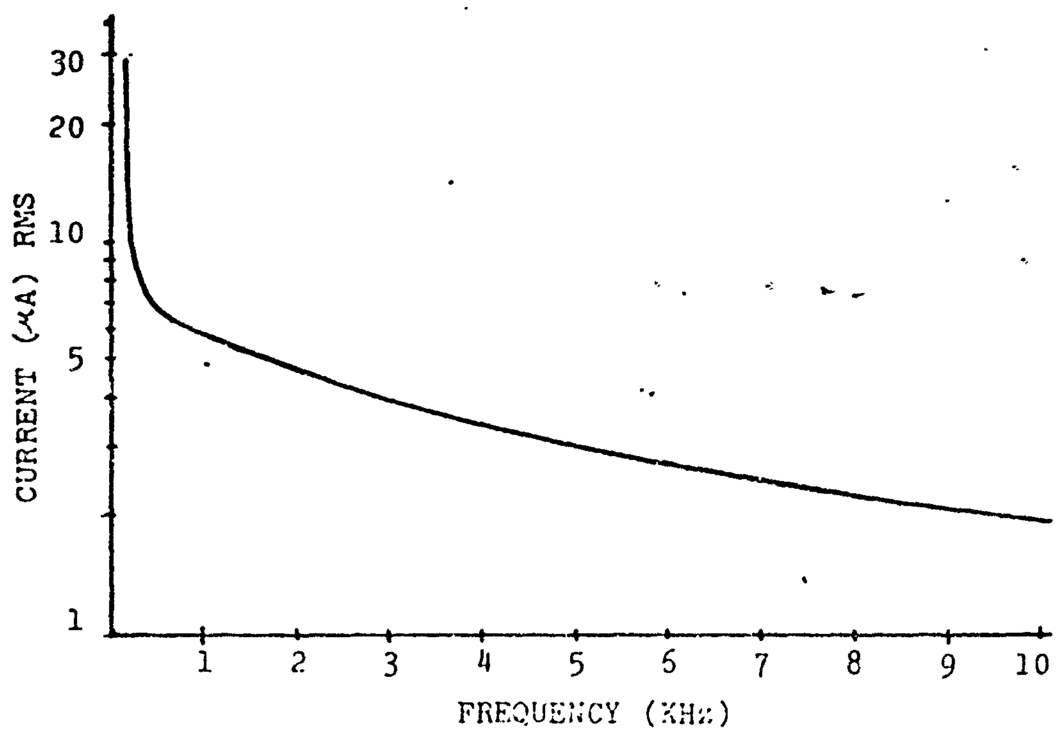

Figure 10. Current vs. Frequency for Electrophonic Effect

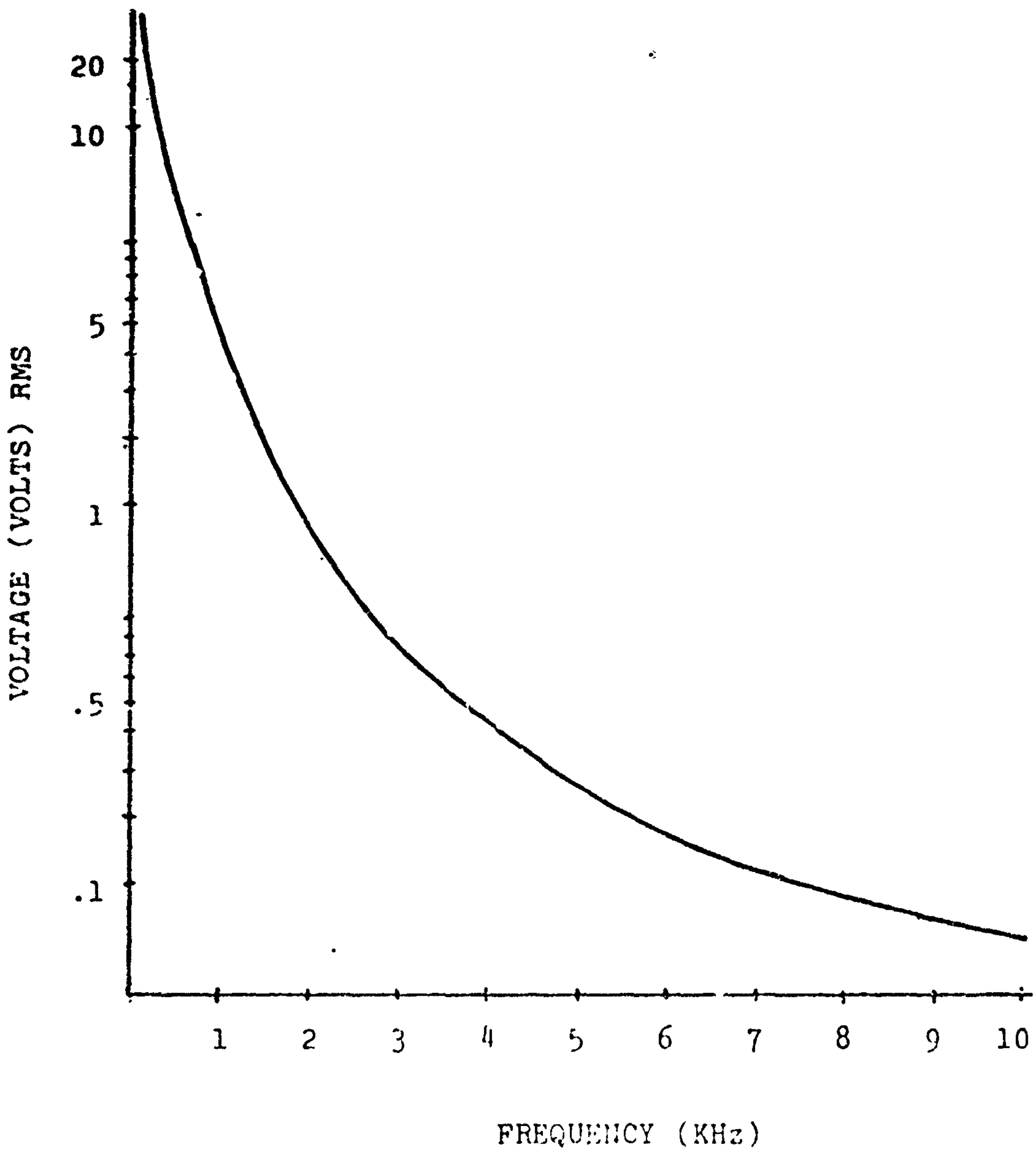

Figure 11. Voltage vs. Frequency for Electrophonic Effect

Current is the major parameter in most biological electrical systems. This is borne out in the graph of threshold. From ≈ 250 Hz to 10 KHz the current required for threshold of a single tone is ≈ 20μA. In order to have enough power margin to handle a band of frequencies, the amplifier built for the desired receiver was a 500 μA constant current amplifier [App.E].

Results of the receiver were good to excellent. Speech and music were easily and well recognizable. A slight tinniless was observed due to the attenuation of frequencies below 250 Hz.

The magnitude of the perceived sound was such that it could be masked by background noise. Further development is necessary to determine the key parameters and to establish the trade offs for magnitude optimization. Further research is indicated to establish the nature of the biologically dependent transduction at the surface of the skin.

Thus it has been shown that using an extremely simple circuit utilizing only microwatts of power, that a small self contained electro-aural transducer can be built.

The applications are obvious and immediate. They range from the possible replacement of the standard Navy headset to the possible replacement of all types of bone conduction hearing aids.

VI. SUMMARY

A. NEW RESEARCH OF THIS PROJECT

1. Audio and Radio Frequency Addition

This type of biasing, similar to that of tape recorded systems yielded results very similar to that of audio plus a D.C. bias.

2. Ionic Electrodes

Wet Ag•AgCl electrodes, when used as a pair, bypassed, in large part, the surface impedance and capacitance of the skin.

By saturating the skin with a KCl solution and applying the wet electrodes, the impedance of the electrode skin interface is reduced to a point approaching that of the impedance of implanted electrodes.

It was observed that, in all cases using the ionic electrodes as a pair, the electrophonic effect ceased to exist. This indicates that the location of the electrophonic effect is the top layers of skin, the dermis and/or edpidermis.

B. THE ELECTROPHONIC MECHANISM

The mechanism of electrophonic hearing can be compared to the electro-static action of a capacitor whose plates are separated by a variable distance. Under the influence of an alternating current the plates of the capacitor will vibrate at the frequency of the applied current.

Using pairs of identical electrodes to the head, as in previous research, the comparison of the electrode/head system to that of an electro-static capacitor is shown below:

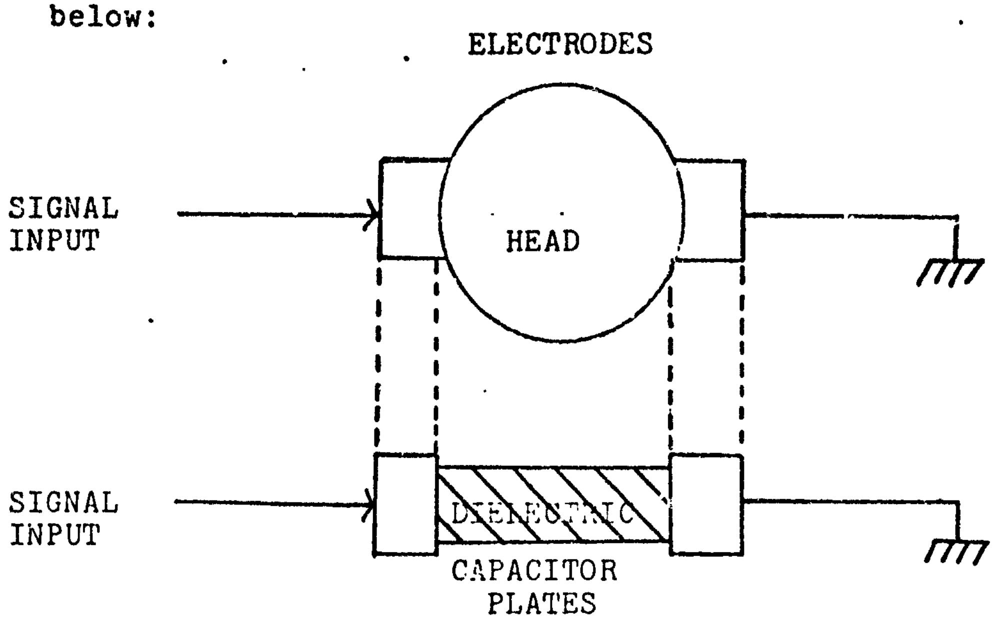

Figure 12. Capacitor Analog Using Pair of Capacitive Electrodes

Using the combination of ionic and capacitively coupled electrodes, the same comparison is shown below:

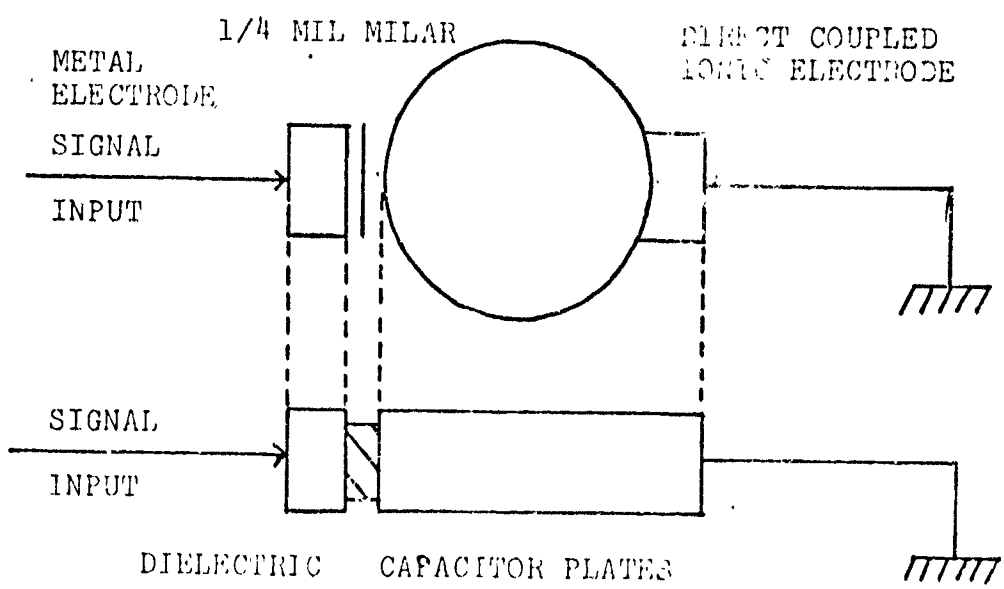

Figure 13. Capacitor Analog Using Hybrid Pair with Ionic Electrode

The mechanical vibrations of the capacitor are dependent upon the magnitude of the applied signal and the attendant electrical field.

The field varies directly with the distance between the plates, or the thickness of the dielectric.

By using the hybrid electrode system, the thickness of the dielectric has been reduced from the width of the head to 1/4 mil. This large decrease in dielectric thickness allows a corresponding large decrease in current magnitude required to provide a field adequate to cause vibrations, and, subsequently, audition.

In all configurations tested, beat frequencies could be observed when one signal generator provided an electrophonic stimulus while another signal generator, at a slightly different frequency, was connected to a speaker.

This indicates that both the electrophonic signal and the pressure wave from the speaker activate the same cochlear elements. This being the case, it is concluded that the basic mechanism of the electrophonic phenomena is mechanical excitation of the top layers of skin in response to an electrical field and bone conductive of these vibrations through the temporal bone causing mechanical motion of the same cochlear elements used in normal hearing.

APPENDIX A

PREPARATION OF IONIC ELECTRODES

Ionic electrodes are formed by plating silver chloride onto silver.

A punch was used to cut 0.75" diameter silver discs from a sheet of silver foil.

The discs were placed between two pieces of optical grade glass and weighted to ensure flatness.

An electrical lead was then soldered to the disc.Heating the disc gently over a Bunsen burner removed the silver oxide.

Clear dope was then applied to the lead and the lead side of the disc to cover the soldered joint. This is necessary to keep the lead metal from contaminating the plating process.

Bakelite discs, with a hole for the lead were then glued onto the silver discs to provide structural strength.

The surfaces were prepared for plating by cleaning with a commercial grade silver polish, followed by soap and water, and finally alcohol.

The discs to be plated are tied to the positive terminal of a 4.5 battery and inserted into a 1 molar solution of KCl or NaCl.

A clean silver strip is connected via lead wire (also covered with dope) to the negative terminal.

Current flow and plating action will start immediately.

Approximately one minute is sufficient to provide a $\approx$ 5 mil plate.

APPENDIX B. TRANSDERMAPHONE

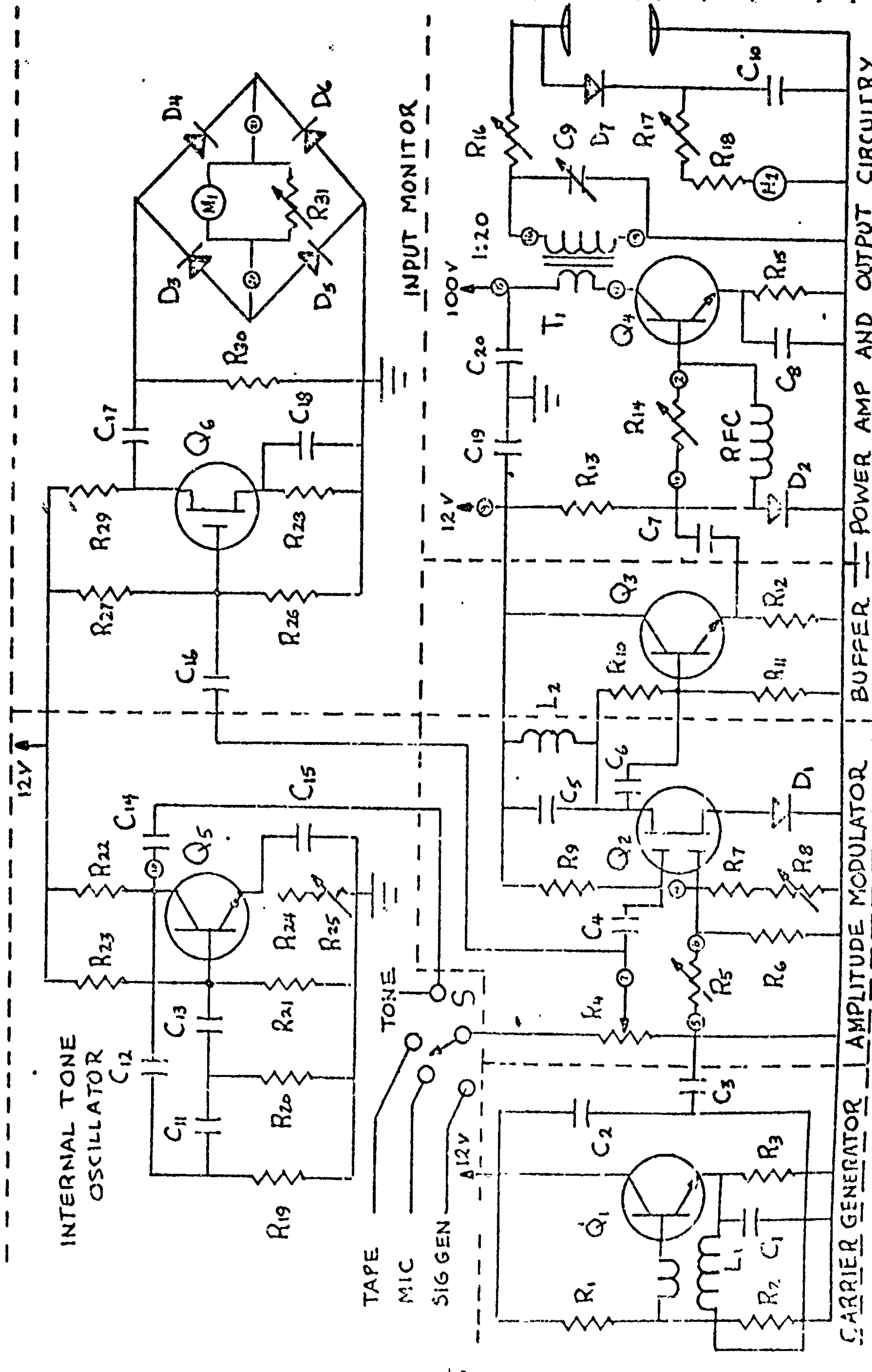

Figure 14(A). Transdermaphone Schematic

COMPONENT VALUES

R_1 ------- 39K	C_{15} ------50
$R_{2,23,30}$ -51K	C_{17} -------6
$R_{3,24,29}$ - 2K	C_{18} -------2
R_4 ----- 500K	$C_{19,20}$ -100
R_5 -------- 2M	
R_6 ------ 2.4M	$D_{1,2}$ ----Si
R_7 ------- 22L	D_{3-6} -1N126
R_8 ------- 50K	D_7 --1N1733
R_9 ----- 750K	
R_{10} ---- 240K	Q_1 --2N3417
R_{11} ---- 560K	Q_2 ---3N141
R_{12} ---- 3.6K	Q_3 ---2N736
R_{13} ----- 10K	Q_4 --TIP 27
R_{15} ------- 22	Q_5 --2N3710
R_{16} ---- 7.5K	Q_6 ---40468
R_{17} ------ 1M	
R_{18} ----- 11M	L_1 --50-100mh
R_{19-22} -- 11K	L_2 --990µh-1.87mh
R_{25} ------ 5K	
R_{26} ---- 4.7M	$M_{1,2}$ --50µamp d-c
R_{27} ----- 22M	
R_{31} ---- 100K	
$C_{1,8}$ ----- 50	
C_2 ----- .003	
C_3 ---- 360pf	
$C_{4,16}$ -- .025	
C_5 ---- 500pf	
C_6 ---- 300pf	
C_7 ------- 10	
C_9 --20-160pf	
C_{10} --- 2.5pf	
C_{11-14} -.0033	

NOTES:

1. All capacitances are in microfarads unless otherwise stated.

2. Circled numbers on both diagrams depict pin connections on the plug in circuit board.

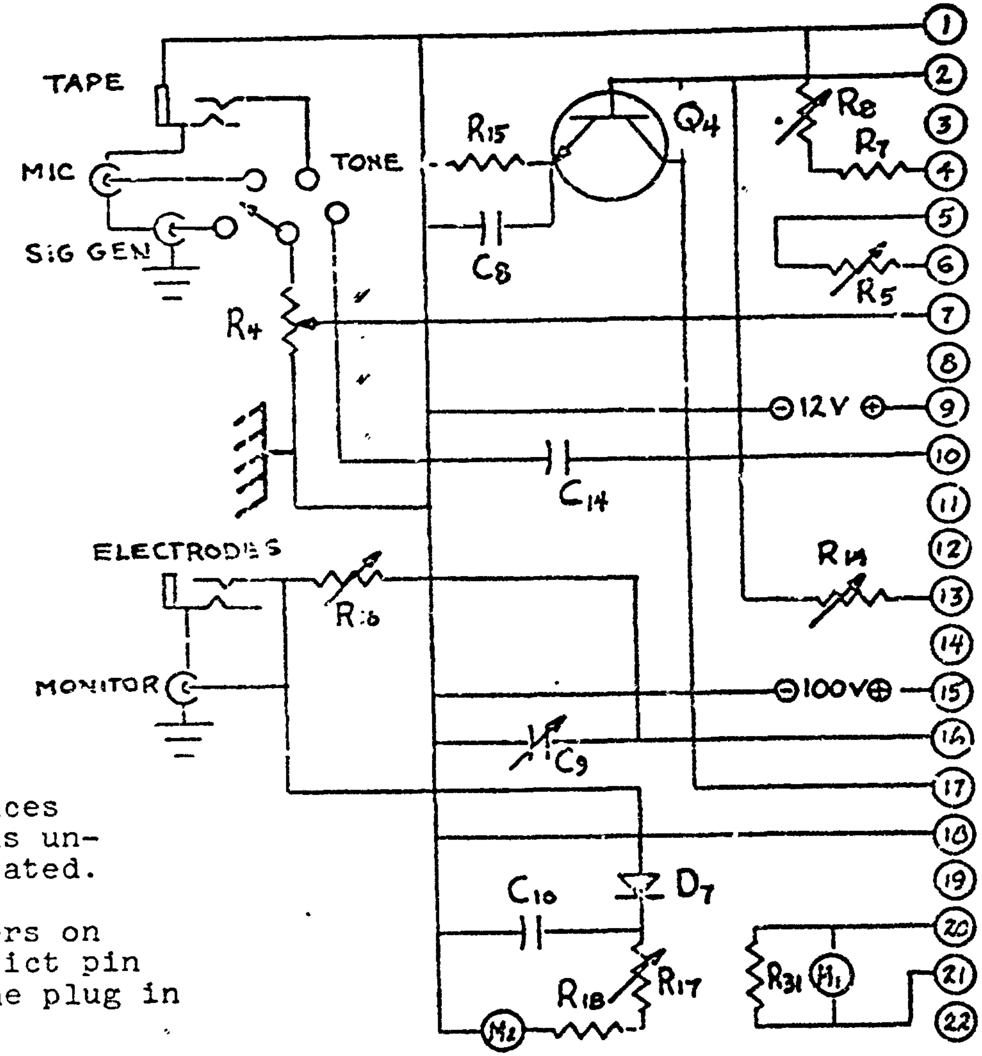

Figure 14(B). Transdermaphone Schematic

APPENDIX C

RADIO FREQUENCY PLUS AUDIO ADDITION (WITH OR WITHOUT D.C BIAS)

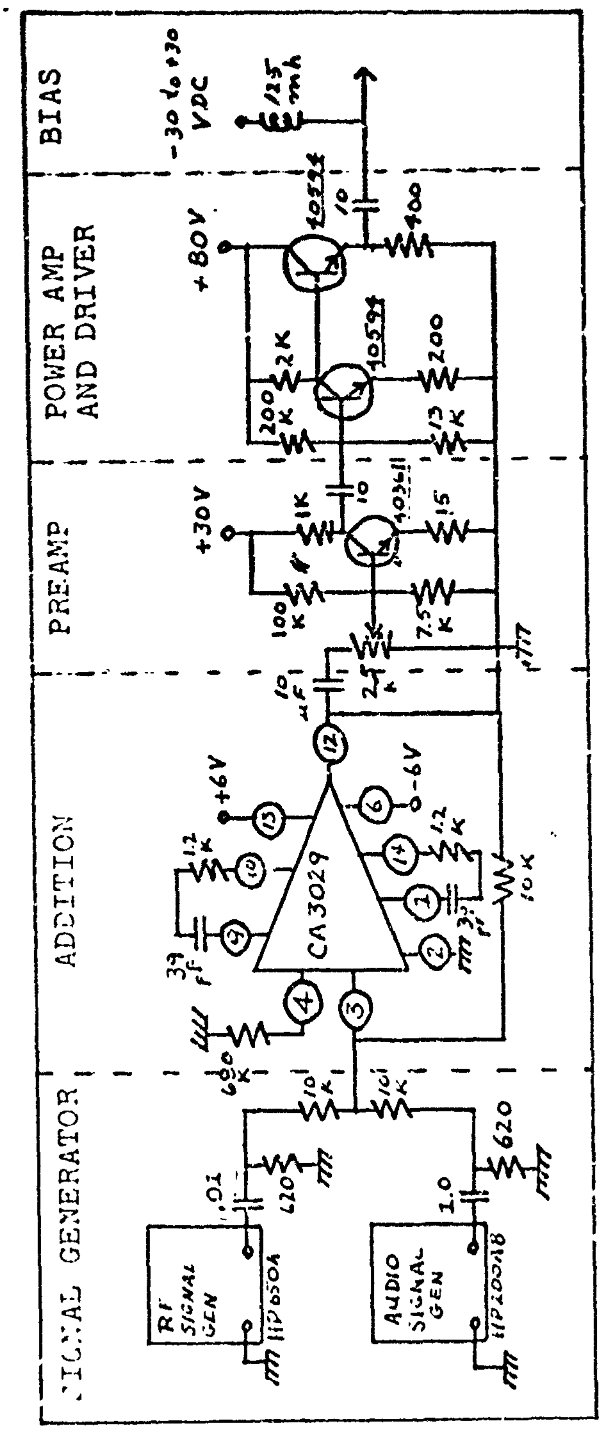

Figure 15. Circuit Schematic

APPENDIX C

AMPLITUDE MODULATION (WITH OR WITHOUT D.C. BIAS)

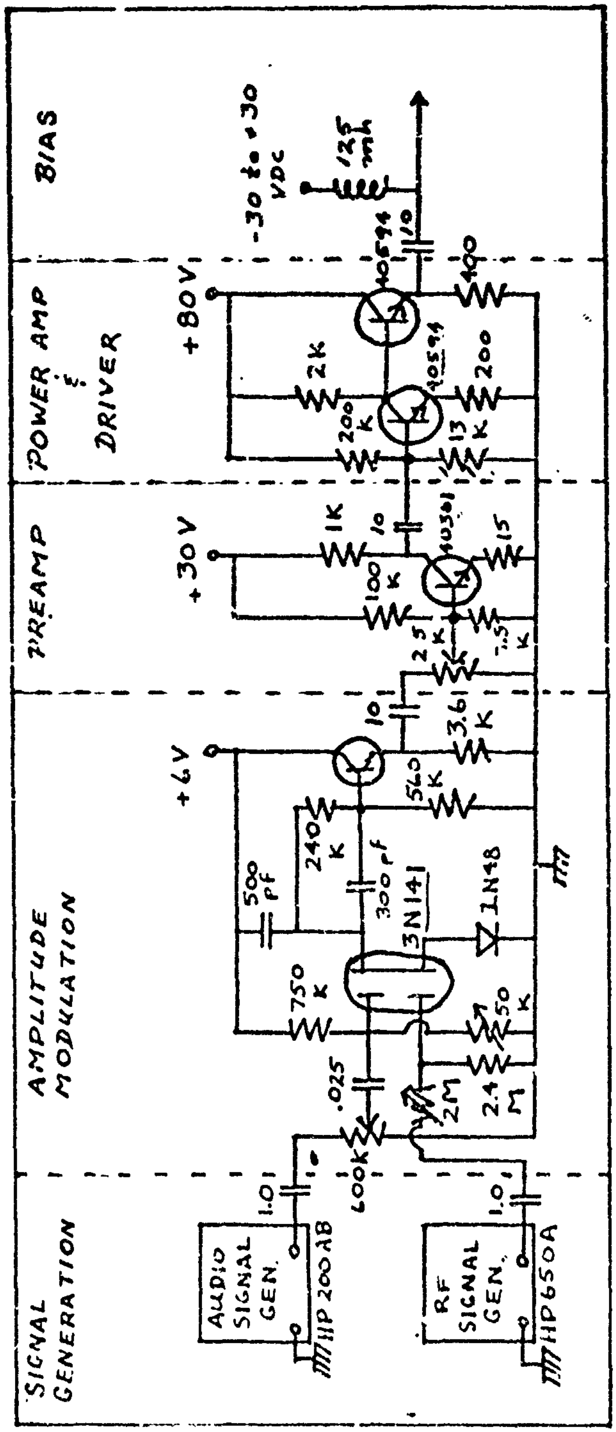

Figure 16. Circuit Schematic

APPENDIX D

INSTRUMENTATION

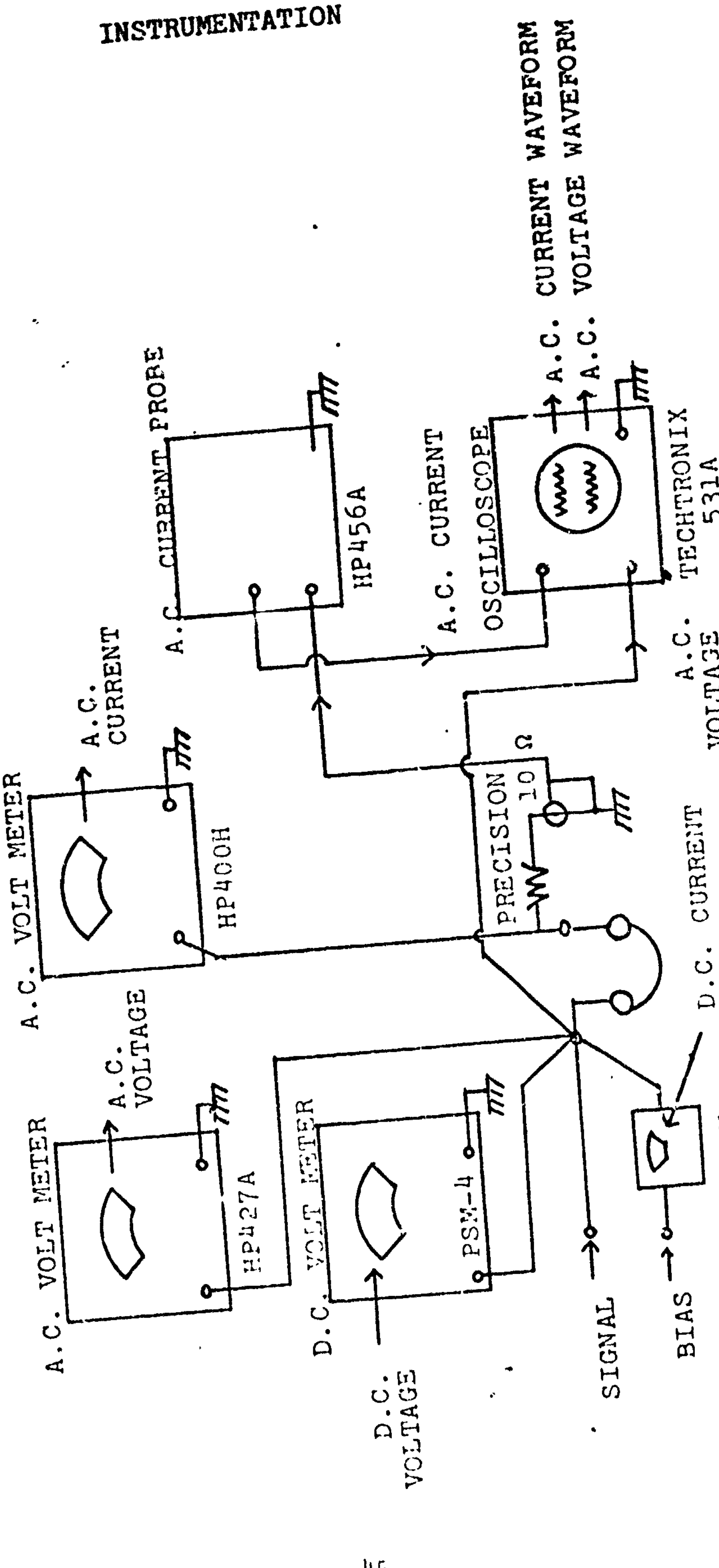

Figure 17. Experimental Instrumentation

APPENDIX E

ELECTROPHONIC RECEIVER

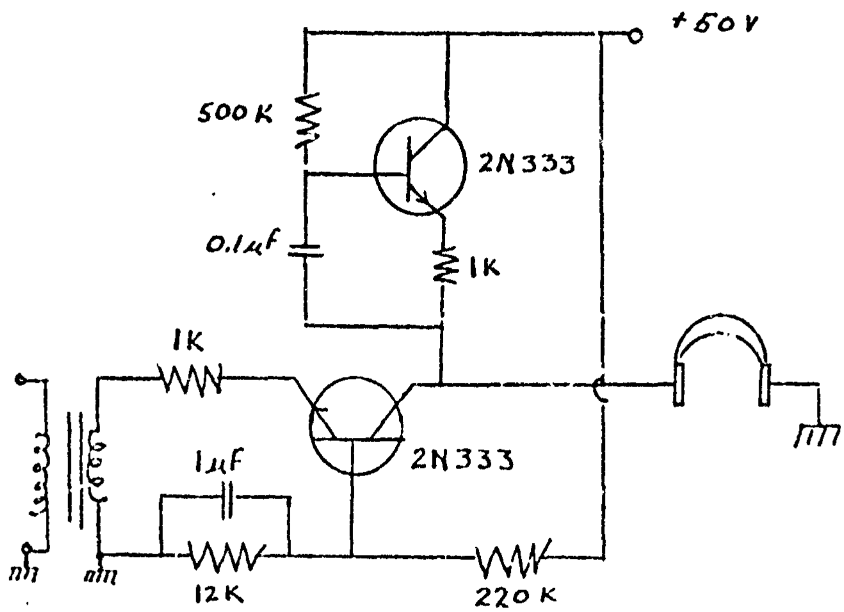

Figure 18. Constant Current Amplifier Schematic

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13. ABSTRACT

The physiological sensation of hearing can be stimulated by an alternating current applied to the head using small electrodes. The major disadvantages of systems of this type have been the large magnitude of driving voltage required, ~ 100 to 4000 volts, and the magnitude of power dissipated in the head, ~ 1 watt.

The objectives of the paper were to investigate the basic phenomena and to attempt to find a low power method for production.

Previous successful experiments were reproduced during the basic investigation phase. Selected combinations of signal types and electrodes were then tested.

An extremely low power mode of operation was found and documented. Threshold values for a single tone were found to be in the order of 10μA at 10μWatt making an extremely small low cost hearing aid a possible application.

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Electroaudition						
Electrophonic Hearing						
Transdermal Stimulation						
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Cochlear Microphonics						
Electrical-Aural Transduction						

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